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Plant Leaves for the Production of Oxygen in a Closed System

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One year ago we began evaluating higher plants as a source of food and oxygen and as a sink for carbon dioxide in a closed ecological system. One molecule of O_2 is given off for each molecule of CO_2 fixed in photosynthesis. At that time we employed the results of earlier experiments to predict that 130 $ft.^2$ of sugar cane or maize leaves could supply sufficient oxygen for one man. Since those early calculations, we have obtained rates of photosynthesis double the 50 mg CO_2 dm^{-2} hr^{-1} on which the calculations were based.

The maximum rate which we have observed, 102 mg. CO_2 dm^{-2} hr^{-1}, was attained by sugar cane leaves in 0.1 per cent CO_2 and illuminated with 15,000 ft.c. from incandescent lamps. Maize and sunflower leaves have repeatedly fixed 75 to 85 mg. CO_2 dm^{-2} hr^{-1}. Under ideal conditions, therefore, the 1 $ft.^3$ O_2 hr^{-1} required by a man could be produced by 75 $ft.^2$ of maize, cane or sunflower leaves (NASr-129, First Quart. Report).

Thus we have demonstrated that a few plants under favorable conditions are able to fix CO_2 and produce O_2 much more rapidly than commonly reported. To be practical, however, a closed ecological system must have small weight and volume, be dependable and operate continuously. Therefore, our objective has been maintaining maximum production of O_2 per unit weight or volume.

<u>To reduce weight of the system.</u>

The weight of the plants is but a part of the weight of the total system for O_2 production. Measures have been taken to reduce these other weights. We have used light-weight vermiculite as a rooting medium in our pilot system. Only enough water for the immediate needs of the plants need be supplied since the water is continuously removed from the air by a condenser and returned to the root zone. Because leaf cells of higher plants have membranes which separate the liquid or cellular from the gaseous phase, the closed ecological system can be simple. The chamber in which the plants grow can also be the living

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space of the men or connected directly to it. The plant chamber must be illuminated. The only other equipment needed is a simple condenser to remove water from the air and a fan to circulate the air from any adjacent living quarters through the plant chamber. A pilot system permits the testing of these matters.

To test O_2 production by plants we have constructed a pilot system that will provide O_2 for two men under the ideal conditions mentioned above. This system was described in NASr-129 Third Quart. Rpt. The system consists of the plant chamber, a circulating fan, and a simple condensing coil through which tap water is circulated. The system is lighted by VHO fluorescent lamps mounted at intervals of 3 inches on all four sides; behind the lamps is a chromium reflector. The heaviest components of the system are the ballasts for the lamps, a conponent which could be eliminated if high voltage electricity were available.

The total weight of the plants, water and vermiculite is about 100 lbs. The weight of the enclosure and accessory equipment is about 200 lbs.; this could be substantially reduced by use of lighter weight materials. This, we feel, is an engineering problem and has not claimed our attention. The biological part of the system, the plants, water supply and rooting medium, have been reduced to 100 lbs. because the water transpired by the plants is condensed from the air and returned to the rooting medium. Therefore, a small supply of water is sufficient for the plants, and the air is dried so water does not condense on the chamber walls, in the ducts or in the fan. Thus, the system weighs little because little water is needed, and the necessary accessory equipment is simple.

<u>To reduce volume of the system.</u>

To reduce the volume of the system requires rapid O_2 production or CO_2 absorption by unit area of leaf and packing many leaves in a small space.

Optimum conditions for CO_2 absorption by maize and cane leaves were determined. Of particular promise was the continued response of cane and maize to increasing illumination and carbon dioxide concentrations as shown in Fig. 1 (from work not supported by NASA). The maize leaves responded dramatically to both increasing CO_2 and illumination. Fig. 3 shows the photosynthesis of a cane leaf in intense radiation and varying CO_2. Again, photosynthesis responded dramatically as CO_2 was increased. It increased little, however, beyond 600 ppm CO_2.

The response of the photosynthesis of maize to temperature is shown in Fig. 3. Again, the results were dramatic and clear. As the air cooled below 30 C the rate of CO_2 absorption declined markedly. When the air was warmed to 40°, a somewhat smaller reduction was found.

Thus, we were able to determine optimum conditions for our initial tests of the pilot system: A temperature of 30° C., 0.1 per cent CO_2 and intense light.

In a large system for oxygen production, however, intense, collimated light comparable to sunlight is difficult to obtain. Instead, in our pilot system the illumination is 4,000 ft.c. at all points and from all directions. Thus, it is important to determine the efficiency of 4,000 ft.c. from both sides of the leaf compared to a more intense light of 10,000 ft.c. from above the leaf only, the illumination that has caused the rapid production of O_2 specified in our original proposal.

The photosynthesis of maize leaves was identical whether lighted from above and from below. At all intensities, light was equally effective from either direction. Chloroplasts are evenly distributed throughout the cross-section of a corn leaf and light from below and light from above were expected to be absorbed by about equal quantities of inert material and hence about equal amounts of light were expected to reach active pigments from either side.

In contrast, tobacco or sunflower leaves have a palisade layer and greater concentration of chloroplasts along the top of the leaves. When light came from beneath the leaf rather than from above, both tobacco and sunflower responded quite differently from corn. When a tobacco leaf was lighted from above and then a dim light from beneath was turned on, the rate of photosynthesis dropped quickly to one much lower than the previous rate.

Stomates were measured when the leaves were lighted from the top only and again after the light beneath was turned on. The stomata on the bottom of the leaf closed when struck by the direct light. In at least one set of measurements the average stomatal apertures changed from 10 to less than 1 micron. This closure was probably due to desiccation of the stomatal guard cells. The closure of tobacco stomates was prevented by moistening the air in the chamber to nearly 100 per cent. Then, at saturating light intensity, top and bottom lighting cause equal CO_2 absorption. All the chloroplasts were receiving all the light they could utilize regardless of the direction from which it came. That is, they were saturated with light. At light intensities below saturation, however, 2,500 ft.c. from the top caused the absorption of 25 per cent more CO_2 than the same illumination from below. Similar results were obtained with sunflower. Thus, leaf structure is apparently important in determining the efficiency of light from beneath leaves. Plants that have chlorophyll evenly distributed throughout a vertical leaf section, such as corn and sugar cane, appear to have an advantage in a system where light comes from all directions.

Of more importance here, of course, are the absolute rates of photosynthesis and of O_2 production by leaves lighted from two sides compared to the maximum rates obtained with intense light from one side of the leaf. A corn leaf, Fig. 4, lighted with 2,000 ft.c. from both above and below had a rate of photosynthesis 89 per cent as great as the maximum rate observed with 6,000 ft.c. on one or both sides of the leaf. In contrast, 2,000 ft.c. from only one direction produced a photosynthesis rate just 57 per cent of the maximum.

The response of efficient cane leaves to light from both above and beneath the leaves is shown in Fig. 5. Once again, lighting both surfaces of the leaf resulted in dramatic increases in photosynthesis in light less intense than saturating illumination. Of particular importance for application in a closed system is the fact that high absolute rates of photosynthesis were attained in illumination of less than 5,000 ft.c. Similar results were obtained with tobacco and sunflower. Thus, weaker light on all surfaces of the plant has much the same effect as intense light from above. These are particularly promising results since our pilot system is completely surrounded with lights, including a light in the center of the chamber. Thus since the light comes uniformly from all angles, many leaves can be packed into the system before shading becomes a problem.

It now remains to test maize, cane and sunflower in the plant system to see if high rates of O_2 production by many leaves can be attained and maintained.

Continuous O_2 production.

Plants require light to produce oxygen. Therefore, it would be desirable for a plant system to operate in continuous light. Normally, however, plants have a period of darkness each day. For example, a period of darkness is required for normal growth and development of tomato. It was necessary, therefore, to test the candidate plants - sugar cane, maize and sunflower - in continuous light.

Several experiments have been performed using both fluorescent and incandescent lights. Under incandescent lamps, continuous light of any intensity destroyed chlorophyll, and the rates of O_2 production decreased (NASr-129 Second and Third Quart. Reports).

Fluorescent lights have, however, shown promise in two experiments. In the first experiment a 2-ft tall sugar cane and a 6-inch tall tomato plant were placed in a chamber 1-ft square and 9-ft tall; it had a single "Power-groove" fluorescent lamp placed vertically in the chamber and an aluminum reflector around the outside. The plants were grown in vermiculite. Corn and sunflower were planted in the vermiculite.

As expected, after 3 days the lower leaves of the tomato plant became chlorotic because the light was continuous. This chlorosis increased until after two weeks the plant was nearly all yellow. At the end of one month, the plant was nearly white, and during the following week, it died.

In contrast, the cane grew normally. The corn and sunflower grew slowly in the dim light but did not become chlorotic. After 60 days, the corn and sunflower were removed. The cane continued to grow until the experiment was terminated after 6 months.

In the second experiment which has not yet terminated, we are growing cane in our pilot system in 4000 ft.c. illumination from fluorescent lamps. The cane has been illuminated continuously for 60 days with relatively little bleaching of the chlorophyll. Thus, changing the spectral composition of the light promises to be a solution to growing cane in intense, continous light.

Summary of first year of contract NASr-129.

We have screened numerous species of higher plants for use in a closed ecological system. Our primary criteria for selection were maximum O_2 production rate from a unit of leaf area, ease of maintaining and reproducing the plants, their persistence in continuous illumination and ease of lighting many leaves packed into a small volume. A final consideration was the ease with which an edible product could be obtained from the plant.

Many species were eliminated because they yield little outdoors. Others were rejected because they absorbed CO_2 slowly. Among these were many trees and such common crops as orchard grass, red clover and tobacco.

Further experiments were conducted with the three most promising species - maize, sugar cane, and sunflower. Our choice for initial tests in our pilot system was sugar cane. It has the highest O_2 production per unit leaf of any plant we tested, can be grown as a perennial and can be quickly started from the root system. Thus, new plants need not start from seed. The growth habit of cane allows many leaves to be confined in a small volume. Further, cane appears to withstand continuous illumination from fluorescent lamps without harmful destruction of chlorophyll. Finally, much of the CO_2 that is fixed can easily be extracted as digestable carbohydrates.

The optimum conditions for O_2 production by cane have been determined. We found that high rates of CO_2 absorption could be ahcieved by lighting both surfaces of leaves with the illumination that exists in our pilot system. A temperature of 30 C and 0.1 per cent CO_2 in the atmosphere were ideal; these conditions would not harm men enclosed in the system.

The closed system that employs sugar cane to produce O_2 and consume CO_2 can be simple and weigh little. Since leaves have membranes which confine the active cells, and since no toxic substances are released into the atmosphere by cane, the system does not need filters or complicated membrane pumps such as would be necessary for single-celled aquatic plants. A source of illumination, a simple fan to circulate the air through the quarters of the men and back to the plant chamber, and a simple condenser to remove water from the air and return it to the roots are the only accessory equipment needed. Further, the plants can be grown with little water about their roots. Thus, the total weight and complexity of the system can be low.

We have constructed a closed system that may support 2 men. We inject CO_2 gas as animals would supply it. Currently we are testing production rates of cane in this system, ways of managing and harvesting the growth without disrupting the system, and ways of maintaining a proper nutrient balance for the plants. We anticipate estimating the human nutritive value of the plant growth both by chemical means and by feeding the product to rats.

Figure 1. Response of maize leaves to light at different concentrations of carbon dioxide. (From "Variation in the response of photosynthesis to light" by John D. Hesketh and Dale N. Moss. Crop Science 3:110. 1963.)

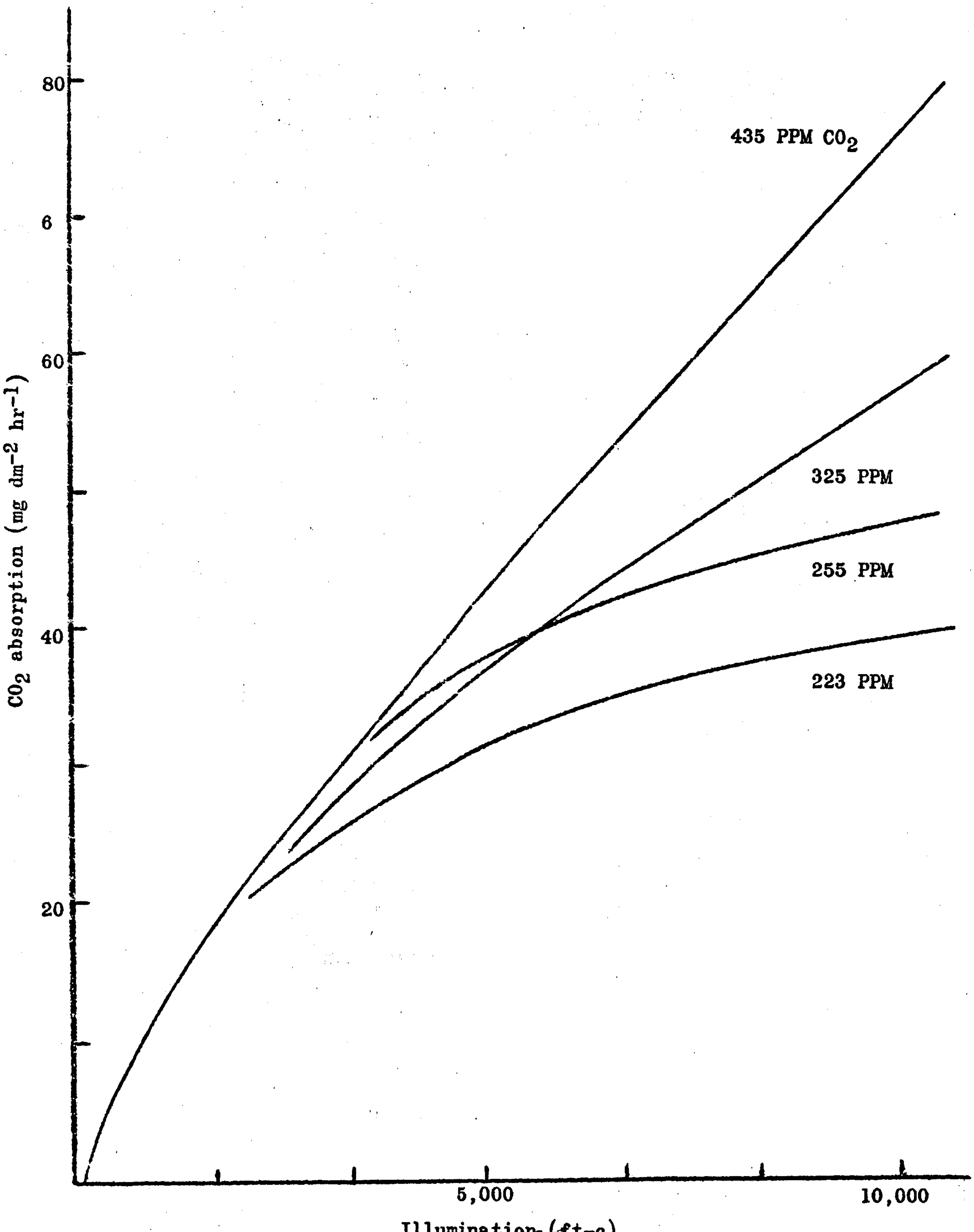

Fig. 2 The effect of temperature and CO_2 on photosynthesis of corn

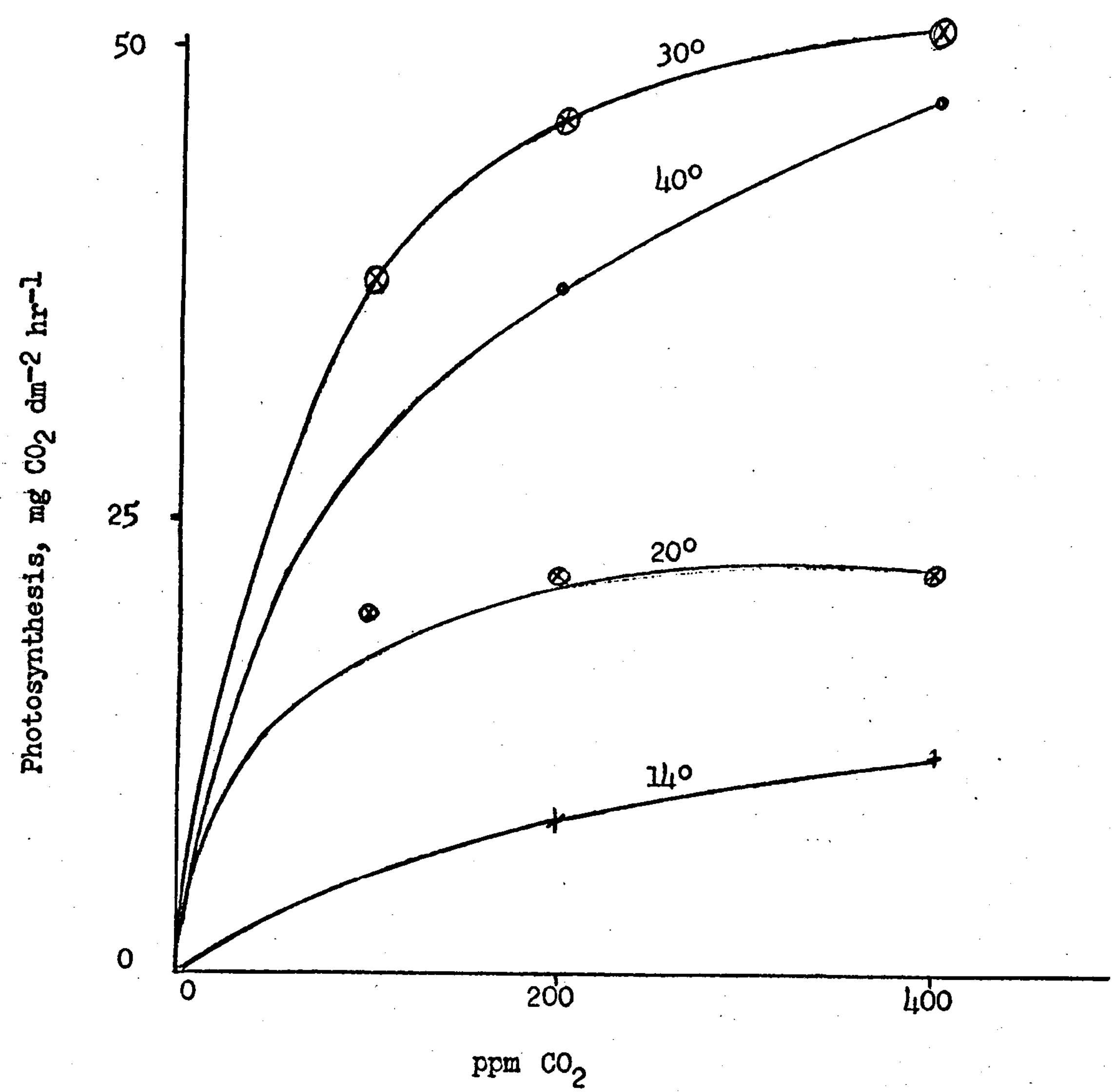

Figure 3. CO_2 absorption of sugar cane as a function of CO_2 concentration single leaves - 15,000 ft-c

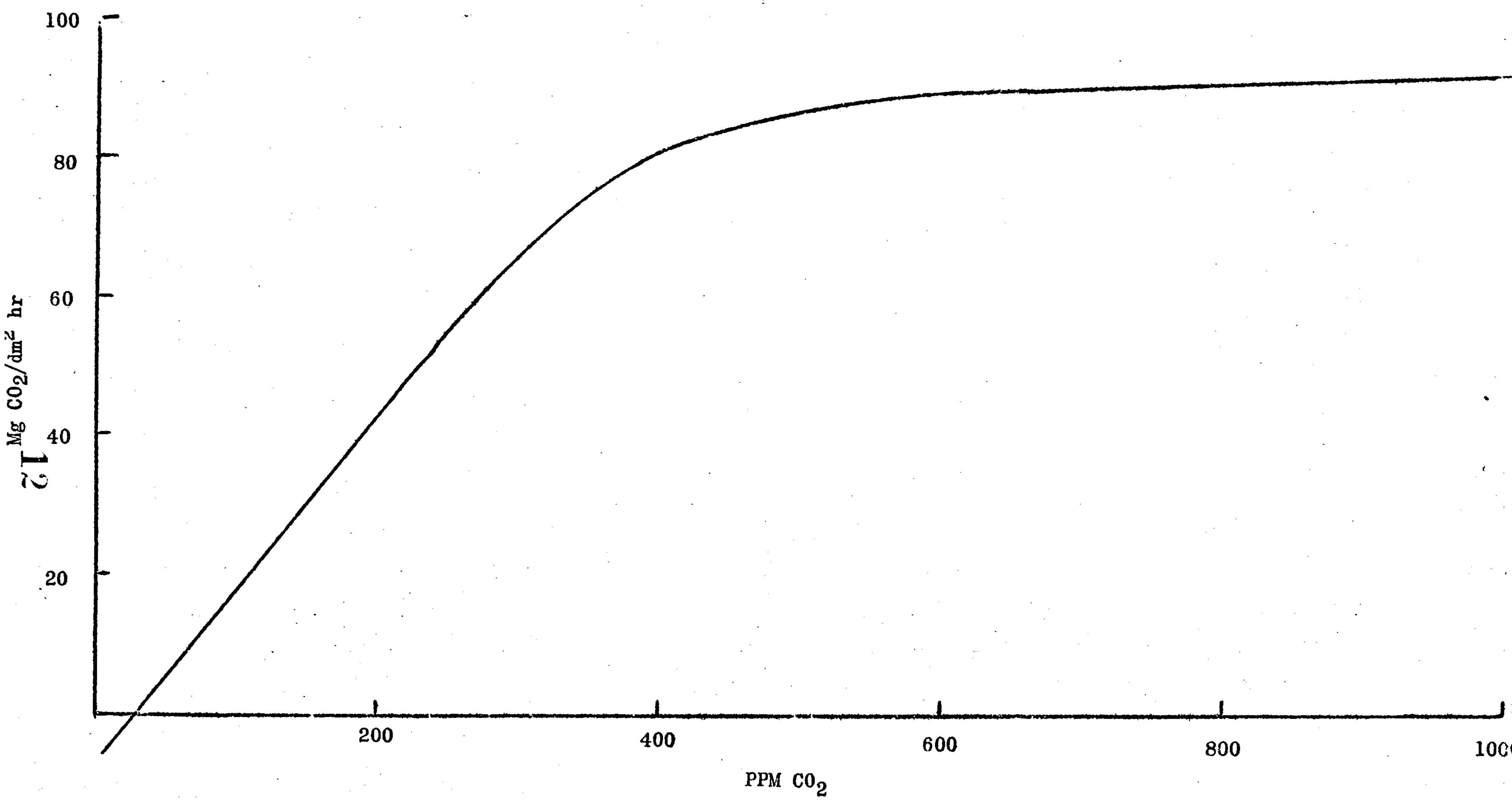

Fig. 4. Photosynthesis of maize leaves (mg CO_2 dm^{-2} hr^{-1}) lighted from above or beneath. The air contained 300 ppm CO_2.

Bottom Light Intensity, ft.c.	Top Light Intensity, ft.c.: Off	1,000	2,000	3,000	6,000
Off		9.6	15.1	19.4	24.2
1,000	9.3	16.7	18.3	21.2	23.8
2,000	15.1	20.9	23.6	25.0	26.7
3,000	21.7	24.5	23.5	24.4	26.7
6,000	26.7			26.7	26.4

Fig. 5. Photosynthesis of sugar cane leaves (mg CO_2 dm^{-2} hr^{-1}) lighted from above or beneath. The air contained 300 ppm CO_2.

Top illumination, ft.c.

Bottom illumination, ft.c.	Off	600	1000	1800	3100	5500	9000
Off		11.7	19.5	28.7	39.0	46.8	54.3
600	11.2	22.6	31.9				
1000	18.7			40.5			
1800	24.9				50.6		
3100	39.7					54.2	
5500	46.0						